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Coastal Meteorology Science Plan

by

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During the warm season along the U.S. West Coast, the typical northwesterly winds occasionally reverse to a southerly direction in a narrow zone along the coast. These coastal wind reversals are associated with the rapid return of marine stratus along the coast and have been attributed to the propagation of coastally-trapped disturbances up the coast. The scientific issues surrounding the initiation, propagation, and decay of these disturbances are the primary focus of the Coastal Meteorology Accelerated Research Initiative of the Office of Naval Research. This document highlights the key issues and required observations in order to resolve some of the outstanding issues for these disturbances.

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COASTAL METEOROLOGY SCIENCE PLAN

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1. Introduction

The coastal mountains that extend along virtually the entire length of the U.S. West Coast represent a barrier to the lower-tropospheric flow. Their interaction with the synoptic scale flow gives rise to a variety of mesoscale, trapped atmospheric phenomena within approximately 100 km of the coastline. These features greatly influence the weather of the coastal zone; unfortunately, they are not resolved adequately by the present observational network, and current operational numerical weather prediction (NWP) models are unable to realistically simulate their evolution. A large number of theoretical ideas have been proposed to explain the mesoscale features of the coastal zone, but few have been tested with data sets of sufficient completeness and resolution.

The planned study of coastal mesoscale meteorology along the U.S. West Coast should yield important practical and scientific benefits. Practical benefits include more accurate short-term marine and aviation forecasts in the coastal zone, a region of significant importance for both economic and national security reasons. Scientific benefits include understanding the interaction of the synoptic scale flow and real topography, and in resolving the outstanding controversies regarding the dynamic nature of trapped phenomena of the coastal zone.

This document describes the primary scientific issues associated with the interaction of atmospheric circulations with topography along the U.S. West Coast and presents the scientific plan to resolve these issues. Section 2 describes the state of our present understanding topographically trapped flows that occur during the warm season and topographically induced effects associated with landfalling storms during the cool season. Key gaps in our understanding and outstanding questions are highlighted in this section. Section 3 presents scientific hypotheses to be tested through the course of this study and in particular highlights those hypotheses that will be addressed through field observing periods during the early winter of 1995/1996 and the summer of 1996. Section 4 describes the measurement requirements for both these efforts.

2. Scientific Background

The orography along the west coasts of continents can strongly influence the local coastal weather in both the summer and the winter. There are notable differences between the two seasons, but also some similarities regarding terrain effects. The two most important distinctions between the two seasons are the magnitude of the low-level stratification and the frequency of synoptic-scale surface low pressure systems. The winter is typified by frequent landfall of synoptic storm systems and a continuously-stratified lower troposphere, while the summer features much less storm activity and generally a well- defined shallow marine boundary layer (MBL). During the summer, the tilt in a strong low-level inversion causes large cross-shore pressure gradients and a coastal jet for northwesterly flows. The prevailing northwesterly flows are periodically disrupted by coastally-trapped disturbances, which produce southerly flows. During the winter, the continuously stratified lower-levels give rise to mesoscale lee troughs and/or windward ridges that can produce enhanced coastal winds and other mesoscale structure in association with some synoptic-scale systems and fronts. While coastal trapping predominates during the summer and effects due to flow over topography predominates during the winter, lee troughing may be important during the summer and coastal trapping may occur in the high stability regions ahead of some fronts. For both seasons, the mesoscale coastal phenomena that are caused or influenced by the orography are dependent on the large-scale background flow, may be characterized in terms of parameters such as the Froude number, and often include the interaction of adiabatic and non-conservative effects. The outstanding problems related to orography for both seasons involve time-dependent factors.

Characteristics of Warm Season Phenomena

Coastally trapped mesoscale disturbances that propagate up the West Coast are one of the most important weather phenomena during the warm half of the year. In strong cases, a period of less than an hour can bring a wind shift from moderate northerlies (0-10 m/s) to southerlies of 15 m/s or more, temperature falls exceeding 10 deg. C, abrupt pressure rises, and a shift from clear conditions to stratus and fog. An example of these abrupt transitions is shown in Fig. 1. These disturbances disrupt the more typical northwesterly coastal winds that are also trapped by the coastal mountains. Along some portions of the coast, these northwesterly winds can reach 20 m/s in a coastal jet. This study will primarily focus on the issues associated with coastally trapped disturbances.

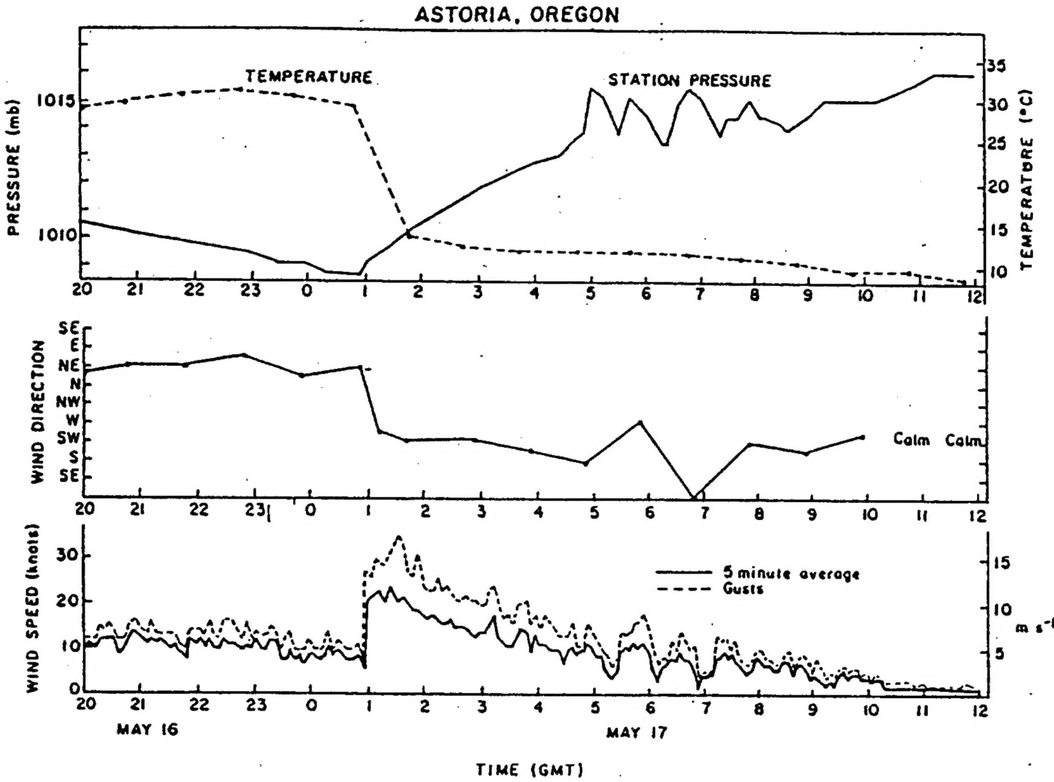


Fig. 1. Temperature, station pressure and winds at Astoria, Oregon from 20 UTC 16 May through 12 UTC 17 May 1985. Temperature and wind direction are based on hourly observations; station pressure and wind speed are from continuous recorders. (From Mass and Albright, 1987)

These disturbances have been interpreted in three different ways: as freely-propagating Kelvin waves (Dorman 1985, 1988), as topographically- trapped density currents (Dorman 1987; Mass and Albright 1987), and as the mesoscale response to the alongshore pressure gradients produced by the orography and the synoptic scale flow (Mass et al. 1986; Mass and Albright 1988; Overland and Bond 1994). The relative importance of Kelvin wave and density current dynamics versus the synoptic-scale control has been addressed in the theoretical study by Reason and Steyn (1992), which suggests that both marine boundary layer processes (Kelvin wave or gravity current) and synoptic-scale processes contribute to the initiation and evolution of trapped disturbances. Preliminary results from a pilot field study in June 1994 tend to confirm that both well defined synoptic-scale forcing and Kelvin wave dynamics contributed to the one coastally-trapped disturbance observed during this period. Although coastally-trapped disturbances may contain components of all three processes, the individual interpretations about the governing dynamics have

important implications about the structure, initiation and propagation of coastally-trapped disturbances, which provides the basis for the scientific hypotheses presented in the next section.

The Kelvin-wave interpretation is based on the fact that the atmosphere along the U.S. West Coast during the summer months can be approximated as a two layer system with the topography providing a wall along the eastern boundary of the fluid. A propagating wave-like disturbance can be excited along the coast if the marine boundary layer (MBL) is preferentially lifted or depressed to the south along the coast. This can produce a northward moving Kelvin wave that will produce a signature in the surface pressure field due to the depth variations of the MBL. An example of a Kelvin wave in a shallow-water model simulation by Klemp et. al. (1995) is shown in Fig. 2. Linear theory predicts a uniform propagation speed of about 6 m/s (Dorman 1985), which agrees with some observations but disagrees with the non-uniform propagation characteristics observed for some disturbances. These variations in propagation may be the result of non-linear dynamics, topographic gaps, or bends in the coastline. The initiation of a Kelvin wave requires the elevation or depression of the MBL along a particular section of the coast, which has not been explained theoretically or documented observationally. A likely candidate initiation process is the lifting that occurs ahead of an upper-level synoptic-scale trough. However, the localization of this lifting to spawn a Kelvin is not clear.

The gravity current or internal bore interpretation is based on the idea that a deep cool mixed layer often exists to the south along the coast with little or no mixed layer further north. Under these conditions, the deep cool air in the mixed layer acts as a source of more dense fluid that subsequently flows northward to push the less dense air out of the way. The signature in the surface pressure field is again due to mixed layer depth differences that occur across the gravity current head. The initiation of a gravity current requires a reservoir of dense fluid to the south, which must be produced in some manner and then released. The typical scenario is for the mixed layer to be substantially reduced in depth to the north due to the passage of a synoptic-scale system leaving substantially different MBL structures to the north and to the south. The reservoir is then released by some unknown event to begin flowing northward. The gravity current should also propagate with a relatively uniform speed that is determined by the density difference across the head of the current. Non-uniform propagation may be the result of along-coast variations in the environmental fluid characteristics. The initiation mechanism has not been identified in the literature but may represent the relaxation of the synoptic-scale pressure gradient due to along-coast variations in the response of the synoptic-scale flow to north-south variations in the coastal topography.

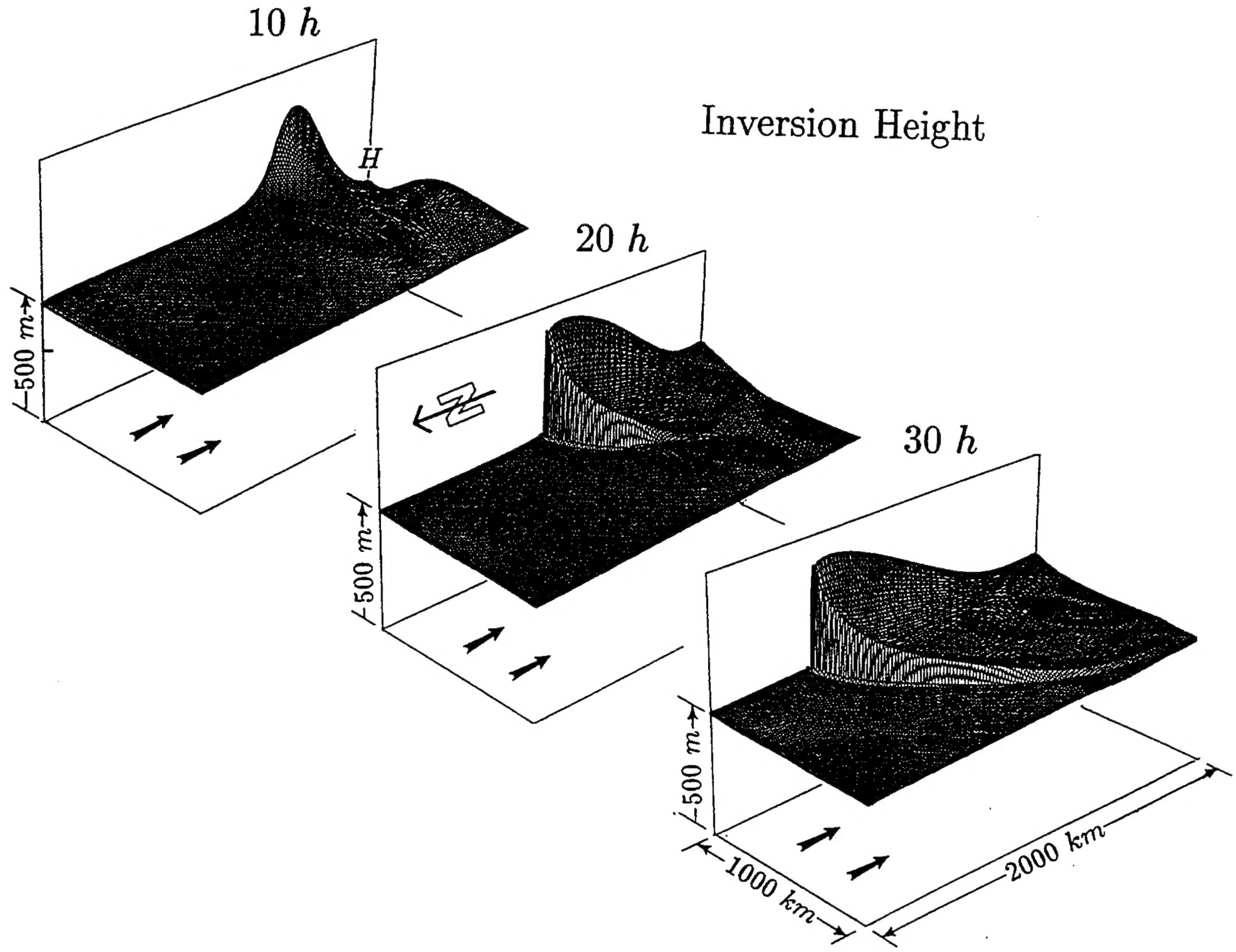


Fig. 2. Evolution of the interface in a shallow-water simulation of a Kelvin wave initiated with a localized pressure anomaly. (From Klemp, Rotunno, and Skamarock, 1995)

The Kelvin wave and gravity current interpretations differ in several clearly identifiable ways. First, the Kelvin wave represents a wave-like disturbance along a relatively uniform mixed layer while the gravity current represents a distinct discontinuity in the mixed

layer depth. Although the internal bore (generalized gravity current) would not have a discontinuous mixed layer depth, the change is considerably more abrupt than that of a Kelvin wave. Next, the gravity current head or leading edge is characterized by considerable small-scale vertical motion that does not occur with a Kelvin wave. Finally, the rapid change in mixed layer depth across the gravity current head will tend to produce air mass differences and different equivalent potential temperatures. The non-turbulent gradual changes associated with the Kelvin wave will not produce an appreciable equivalent potential temperature difference across the leading edge of the wave.

Recent shallow-water modeling studies by Klemp, Rotunno and Skamarock (1994) and Rogerson and Samelson (1995) suggest some important refinements to the Kelvin wave and gravity current processes along the U.S. West Coast. These modeling studies suggest that Kelvin waves can evolve through nonlinear processes to take on gravity current characteristics. Consequently, coastally-trapped disturbances may initially have a Kelvin wave structure and then over time evolve into a more gravity current-like structure. A climatological study by Bond, Mass and Overland (1996) indicates that coastally-trapped disturbances are characterized by more gradual changes in properties to the south along the California coast and by substantially more abrupt changes further north along the Oregon coast. This may be a reflection of this evolution of Kelvin wave disturbances. Another result from the modeling studies is that the shape of the coastal mountains in the cross-shore direction has an impact on the steepness of the leading edge of a Kelvin wave disturbance, which may also contribute to some along-shore evolution in the structure of the disturbance. These modeling studies also suggest that Kelvin wave and gravity current disturbances can propagate around coastal bends of all shapes when the ambient fluid is at rest. How the coastal bends influence the ambient flow is not known and may be a factor in contributing to the observed tendency for these disturbances to stop at some coastal bends. Also important for the decay of these disturbances is that the frictional decay timescale is on the order of 1 day as suggested by these modeling studies. Consequently, the lifecycle of the forcing is of significant interest for longer lived events.

The mesoscale response to along-shore pressure gradients interpretation is based on the idea that orographic and synoptic-scale flow variations along the coast produce mesoscale pressure gradients along the coast that cause southerly winds in particular regions along the coast. In this interpretation the depth of the mixed layer is only important in the sense that it must be sufficiently low to allow air flowing across the coastal topography to descend far enough to produce a topographic response. The basic idea is that as the synoptic-scale pattern evolves, a region of relatively strong offshore directed flow develops along some portion of the coast. As the air flows across the topography, a mesoscale

lee trough develops, particularly in regions of the higher coastal topography such as the Siskiyou Mountains of northern California and the Santa Ynez/San Rafael Mountains north of Santa Barbara. The amplitude of the lee trough is dependent upon the strength and stability of the synoptic-scale flow, both of which vary along the coast. Propagation of the lee trough to the north results from the shift of the subtropical high to the north and east over time. Consequently, the largest negative perturbation pressure propagates north and a zone of southerlies is observed to the south of this feature. In this case, the propagation speed depends upon the movement of the synoptic-scale features which is likely to vary from one event to the next. Differential propagation speeds and abrupt transitions along large portions of the coast are easily accounted for in this interpretation.

A recently completed study by Mass and Bond (1996) of the synoptic patterns associated with coastally-trapped disturbances supports this basic interpretation of the synoptic-scale forcing. Synoptic composites (Fig. 3) show that a trough forms in the lee of the coastal mountains, which results in producing a northward directed sea-level pressure gradient along the coast. This coastal troughing is directly associated with strong offshore directed flow at 850 mb (Fig. 3) and warming of the low-levels in the lee of the coastal topography. Their climatological study does not show any tendency for the coastal troughing to propagate north with time, which may be due to the smoothing that occurs in the compositing process. An important question is whether the resultant pressure gradient in a given situation produces a highly resonant Kelvin wave response. The modeling study of Rogerson and Samelson (1995) suggests that the amplitude of the coastally-trapped disturbance is dependent upon the degree to which the pressure forcing fits a Kelvin wave resonance condition. This may explain why some offshore flow events fail to spawn coastally trapped disturbances.

The development and evolution of mesoscale, stationary troughs in the lee of topography is important for understanding the initiation of these disturbances and are not completely understood. Three different mechanisms have been proposed to explain these lee troughs: (1) downslope, offshore flow forced on the synoptic-scale (Mass and Albright 1987,1988), (2) in the case of the Catalina eddy, a mechanically-induced vortex (Wakimoto 1987), and (3) in the case of Western Australia troughs, differential diabatic heating between the land and sea (Kepert and Smith 1992). At least part of the problem is that previous observational studies have been restricted to the analysis of sea-level pressure changes, and have not been able to resolve the vertical structure. The mechanism responsible for the formation of the coastal pressure trough is also important in determining the atmospheric structure along the coast within which a trapped disturbance evolves. This structure may be important in determining the lifecycle and amplitude of the disturbance.

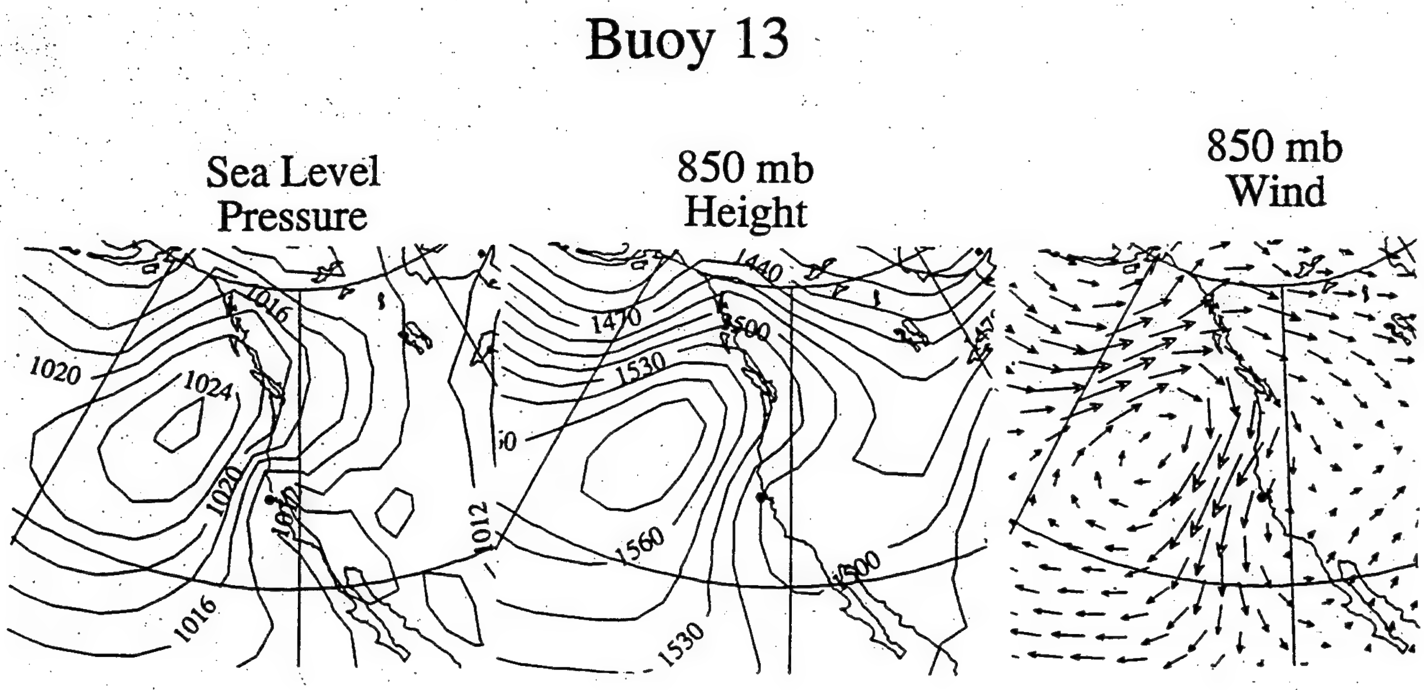


Fig. 3. Composite sea-level pressure, 850 mb height and 850 mb winds over the Eastern Pacific at the time of initiation of southerly transitions at buoy 46013. (From Mass and Bond, 1996)

Preliminary results from the pilot field study of 1994 suggest several important conclusions that require more complete understanding through more detailed field studies and modeling. The coastally-trapped disturbance of June 9-11, 1994 was characterized by a very shallow mixed layer (less than 250 m) and a more complex vertical structure than a simple two-layer fluid. The cross shore structure is shown in Fig. 4 and indicates that the stable layer capping the marine layer spreads vertically near the coast, while the mixed layer depth actually goes down. Although this structure is more complex than a two-layer model, it is favorable for producing a cross-coast pressure gradient that supports geostrophic southerlies in the marine layer. This structure was documented well after the disturbance was initiated and the development of this structure prior to this time is not known. From the synoptic-scale perspective, the initiation of the event did correspond to the development of offshore flow over Central California, although the local generation of a pressure minimum may not be directly due to lee troughing. The development of lower pressure to the north (in Central California) and higher pressure to the south (near

Pt. Conception) preceded the coastal southerlies but the exact mechanism to establish this gradient is not known. An interesting feature of this case is the presense of a weak, low-level cyclonic circulation off the Southern California coast (Fig. 5), which may have contributed to onshore flow and marine layer deepening to set up the favorable along shore pressure gradient, and most certainly accounts for the relatively deep southerly flow (up to 500 mb) along the coast in this case. The development and evolution of this offshore synoptic-scale feature must be understood to understand the synoptic-scale and marine boundary layer interactions in this and other disturbances of this type.

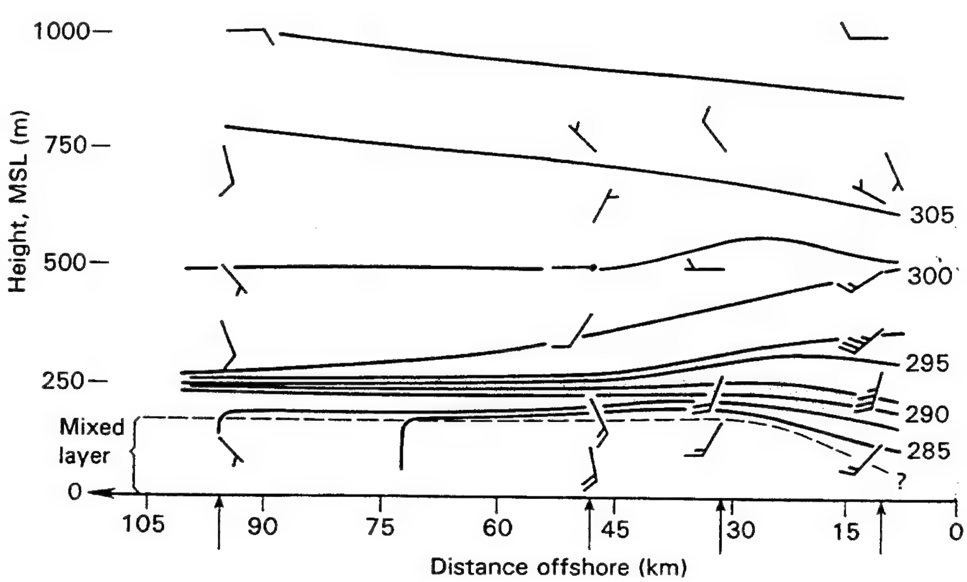


Fig. 4. Cross-shore cross-section based on four aircraft profiles southwest of Monterey Bay between 2047 and 2158 UTC 10 June 1994. Mixed layer top indicated by dashed line. Isentropes are drawn every 2 K and full wind flag is 10 kts and half flag is 5 kts. (From Ralph et. al., 1996)

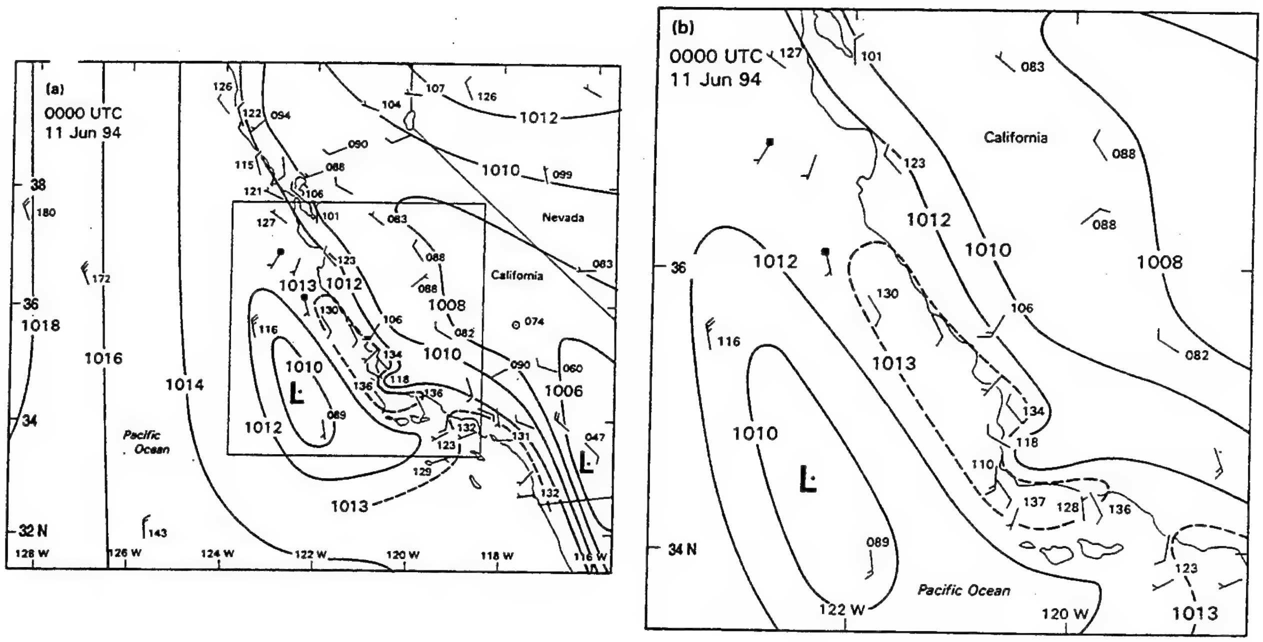


Fig. 5. Surface observations and sea-level pressure analysis at 0000 UTC 11 June 1994. Sea-level pressure contours are every 2 mb except 1013 mb contour which is dashed.(From Ralph et. al., 1996)

Characteristics of Cool Season Phenomena

Enhanced coastal winds and heavy precipitation are the most important weather phenomena during the cool half of the year. Pre-frontal winds in excess of 25 m/s often occur along some portions of the coast in advance of many synoptic-scale low pressure systems and precipitation amounts exceeding 3 inches in a less than 6 hours can cause significant flooding in some areas ahead of an approaching front. While mesoscale along-front variations in the structure of fronts have been well documented over the open ocean, the role of terrain in generating mesoscale structure in synoptic-scale systems is poorly documented and not well understood. Overland and Bond (1994) have documented one case of high winds along the Alaskan coastline that appears to be associated with a propagating pressure surge forced by post-frontal onshore flow. West coast forecasters are aware of the occurrence of pre-frontal high winds as well but have difficulty in identifying the most destructive storms ahead of time.

Two basic mechanisms exist by which the topography may directly influence the storm

structure. For weaker continuously stratified conditions, the component of the flow across the topographic barrier can produce windward ridging and lee troughing effects (Mass and Ferber 1990). The lee trough and/or windward ridge can enhance the pressure gradient as well as alter the low-level baroclinic structure in these regions. For stronger stratifications, the component of the flow across the topography may become blocked which leads to significant downgradient ageostrophic accelerations in the along-topography direction. This effect has not been documented in previous studies of landfalling storms but results (e.g., Overland and Bond, 1995) from the pilot field study (COAST) suggest that this may occur near the coastal topography in some storms. These direct influences by the topography may also contribute to indirect modifications by altering the distribution of latent heating in a storm. Enhanced latent heat release and heavy precipitation may be tied to topographic features or topographically influenced dynamic forcing instead of the internal frontal dynamics more characteristic of the open ocean.

Climatology

Large seasonal changes occur in the weather along the U.S. West Coast. During the summer, the subtropical anticyclone is centered near 40 deg. N. The circulation around this high, and its associated subsidence, produces a shallow MBL along the coast capped by a 10 deg. inversion (Neiburger et al. 1961). In the large-scale mean these conditions extend from about Pt. Conception to the Canadian border. Synoptic activity in the summer tends to be weak; the principal effect of synoptic systems is to modulate the intensity and position of the subtropical high, and perhaps most importantly, control the cross-shore component of the low-level flow. The subtropical high has a mean position south of 30 deg. N during the winter. The coastal weather is dominated by the passage of migratory cyclonic storms and their fronts. The winter MBL tends to be deep (1 km) and capped by a relatively weak stable layer. It is not uncommon for a well-defined MBL to be absent. Most of the precipitation along the coast falls during the winter. These differences between the summer and winter weather have important implications for topographically driven phenomena.

Some climatological results are available on mobile, coastally- trapped disturbances, especially for during the summer. Composite large- scale synoptic analyses have been carried out for onshore surges in the Pacific Northwest (Mass et al. 1986) and for Catalina eddies in southern California (Mass and Albright 1989). CODE provided statistics for the West Coast during spring and early summer of 1981 and 1982. This effort was concentrated near Point Arena along the California coast; Beardsley et al. (1987), Dorman (1987), and

Winant et al. (1987) present time series for this region from CODE that indicate a typical interval of 1-2 weeks between transitions in the alongshore winds. Halliwell and Allen (1987) documented the coastal wind field along the entire U.S. west coast for 1981 and 1982, with a focus on the seasonal variations in the large-scale wind variations. The results from a just completed climatological study based on hourly surface buoy data (Bond et al. 1996) are consistent with the results from the studies cited above. The most important result is that coastally trapped wind reversals (those in whihc the southerly flow is highly ageostrophic and restricted to the coastal zone) occur about 1-2 times a month during the warm season along most of the West Coast as shown in Fig. 6. Roughly one quarter of these reversals have a southerly component that exceeds 5 m/s. These reversals tend to be poleward-propagating from about Monterey Bay northward and in the Southern California Bight. Many alongshore propagating features stop or dissipate at Cape Mendocino. Reversals tend to be more abrupt to the north, with surface characteristics resembling gravity currents.

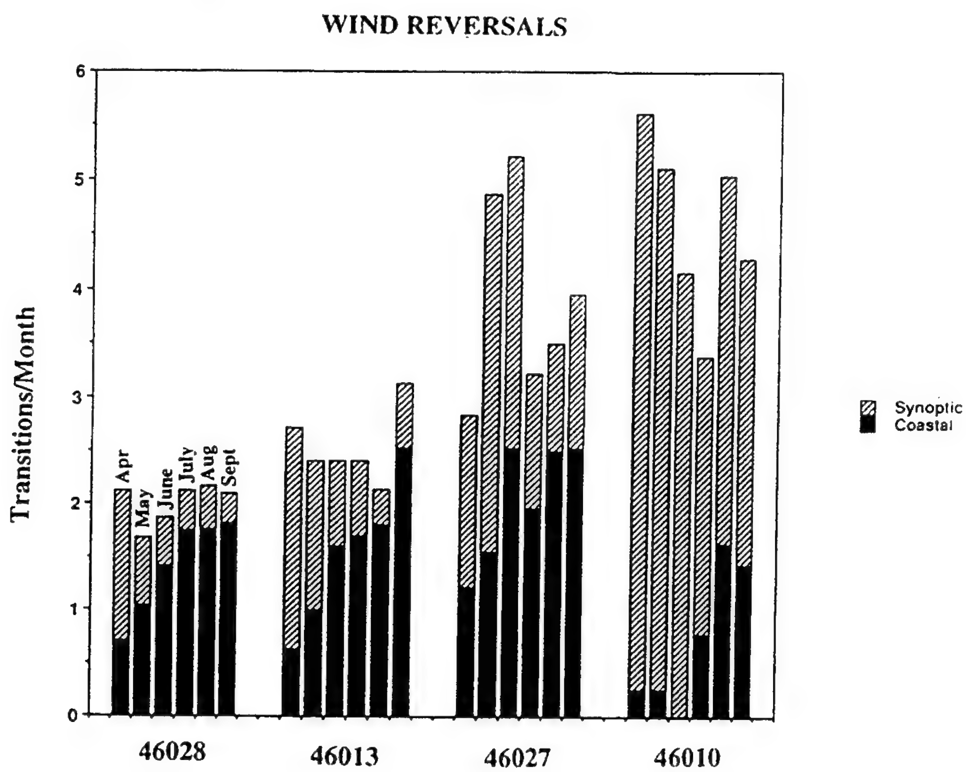


Fig. 6. Monthly frequency of wind reversals for four U.S. West Coast buoys during the warm season. Dark and hatched portions refer to coastally-trapped and synoptic reversals respectively. (From Bond et. al., 1996)

Less is known about the climatology of mesoscale coastal ridging and lee troughing. Ridging events associated with landfalling storms during the cool season would be expected mostly from Central California northward and at a greater frequency than warm-season events, although no climatological studies of this phenomena exist. Mesoscale lee troughing appears to be favored near the border between California and Oregon during the summer. To the extent that the generation and propagation of trapped disturbances is controlled by the large-scale flow, these disturbances are more likely to be associated with coastal ridging events accompanying onshore flow in the winter, and with lee troughing events in the summer. During the late spring both types can occur, with a preference for summer-like events in the south and winter-like events in the north.

There are important mean spatial variations in the MBL. During the summer, the inversion capping the MBL is very persistent along the California coast; this persistence decreases markedly to the north. The height of the summer MBL tends to be at a minimum of 100 m along the northern and central California coast, increase to the north and south, and in the offshore direction. Based on an ongoing analysis of coastal NDBC data (Dorman and Winant 1995), mean wind speed maxima are located of the northern and south- central California coast, with a relative minima between about Pt. Reyes and Santa Cruz. This study also suggests that the coastal wind field is supercritical along a majority of the West Coast from Pt. Conception to Cape Blanco during a significant portion of the summer. During the winter, the mean monthly surface winds are much weaker and more variable in direction (Nelson 1977).

3. Scientific Hypotheses

Coastally-trapped Disturbance Hypotheses

Previous research and preliminary results from a pilot study indicate that coastally trapped disturbances contain a mixture of synoptic/mesoscale forcing, Kelvin wave characteristics and gravity current characteristics. However, the central issue as to whether the northward propagating stratus is a manifestation of a coastally-trapped disturbance remains. Coastal trapping may not be essential to the observed cloud and coastal wind observations. Given that these events are coastally-trapped disturbances, the primary outstanding issues are related to the initiation, evolution and decay of these disturbances and how the three basic elements contribute to or modify the life cycle of coastally trapped disturbances. The following specific hypotheses are aimed at addressing these fundamental issues.

A. Initiation of coastally trapped disturbances

The overall hypothesis regarding the initiation of coastally-trapped disturbances is that the prevailing spring/summer synoptic-scale conditions change to force a coastally-trapped response by establishing a south to north pressure gradient in one of several ways.

i. The synoptic-scale changes in the surface pressure pattern directly force the marine layer and frictional effects are negligible. This direct forcing of the marine layer is hypothesized to be either:

- **a.** a northward directed synoptic-scale pressure gradient that accelerates the marine layer directly down the gradient along the coast, or;
- **b.** offshore winds adjust geostrophically to the synoptic-scale changes to produce cross-coast winds that change the marine layer depth to produce a northward directed along-shore pressure gradient and downgradient flow.

ii. The synoptic-scale changes in the surface pressure pattern force mesoscale flow changes that then force the marine layer. This indirect forcing is hypothesized to be either:

- **a.** the offshore winds act to eliminate the marine mixed layer to the north resulting in northward directed mixed layer depth gradient to produce a south to north sea-level pressure gradient, or;
- **b.** the offshore winds to the north introduce a pulse of frictionally generated potential vorticity from Cape Mendocino that advects south, which induces a cyclonic low-

level circulation with onshore flow to the south that deepens the marine layer there to produce the northward directed mixed layer depth and sea-level pressure gradients.

B. Structure and propagation of coastally trapped disturbances

The overall hypothesis regarding the structure and propagation of coastally-trapped disturbances is that the coastal southerly winds and associated clouds are a trapped response where the dynamic behaviour can be explained in one of several ways.

i. The structure and propagation of coastally-trapped disturbances can be approximately explained from either continuously stratified internal or two-layer shallow-water Kelvin wave and/or rotating gravity current dynamics. From either perspective, the evolution of the Kelvin wave and/or rotating gravity current can understood as either:

a. the Kelvin wave and/or rotating gravity current freely propagating away from a region of forcing that is limited in space and time, such as a lifting or suppressing of the marine boundary layer along a specific section of the coast at a given time, or;

b. the Kelvin wave and/or rotating gravity current results from more continuous forcing over the lifecycle of the disturbance at the natural response of the system (resonance). This continuous forcing is associated with the evolving synoptic conditions.

ii. The structure and propagation of coastally-trapped disturbances can be explained as a mesoscale trapped flow to the south of a northward moving coastal pressure minimum that is due to lee troughing effects along the coastal mountains. From this perspective, the observed marine boundary layer and cross-coast wind structure and propagation are explained as:

a. boundary layer convergence into the coastal pressure trough acting to lift the marine boundary layer to the south of the pressure minimum and an offshore decay in the southerly winds due to the decay of the lee trough away from the coast and the inability of the winds to adjust geostrophically within a Rossby radius of the coastal mountains, and;

b. the propagation is simply a shift in the position of the pressure minimum along the coast due to a synoptic-scale shift in the strongest cross mountain flow and associated lee trough.

C. Decay of coastally trapped disturbances

The overall hypothesis concerning the decay of coastally-trapped disturbances is that the disturbance is stopped by either internal processes that cause the disturbance to spin down or the synoptic-scale forcing changes in a manner that actively opposes the disturbance.

i. Friction at the air-sea interface and the vertical radiation of gravity waves through the stable layer are the primary internal processes that spin down the disturbance when either of the following occurs:

- **a.** the freely propagating Kelvin wave and/or rotating gravity current moves away from the spatially limited region of forcing, or;
- **b.** the background environmental conditions, such as strong northwesterly winds at coastline bends or a strong north to south pressure gradient, act to reduce the synoptic forcing of the disturbance.

ii. The time evolution of the synoptic-scale forcing is such that it no longer forces the disturbance in one of the following ways:

- **a.** the synoptic forcing is no longer at the resonant or natural response for the Kelvin wave and/or rotating gravity current and may actually force decay, or;
- **b.** the coastal lee trough and pressure minimum are eliminated by the synoptic-scale flow shifting to an onshore direction.

Storm Interaction Hypotheses

The key issues associated with topographic influences on landfalling storms during the cool season can be grouped into questions of how the coastal topography modifies frontal structures and dynamics and what impact these modifications have on precipitation.

A. Mesoscale structure

i. The nature of the modification of kinematic, thermodynamic, and precipitation structures accompanying storms, and the spatial scales of these modifications, depend on the static stability, wind speed and direction of the incident flow, and the height and shape of the mountains. In the case of fronts, it will be generally the characteristics of the pre-frontal flow that determine the response to the topography.

ii. Mesoscale along-front variations in the frontal structure within a characteristic distance upstream from the topography are determined primarily by the flow

interaction with the topography and are not influenced by mesoscale frontal structures that occur further offshore.

B. Modification

i. Large ageostrophic accelerations occur on the upstream side of the coastal terrain due to either topographic blocking of the low-level flow in the higher stability region ahead of fronts or windward ridging/lee troughing effects in regions of weaker stability. These large ageostrophic accelerations cause fronts that were in near semi-geostrophic balance over the open ocean to undergo frontolysis on the upstream side of the terrain.

ii. The topographically blocked flow or windward ridging/lee troughing effects alter the mesoscale storm structure by altering mass balance within the storm and by organizing the latent heat release relative to be linked more to the topography than the synoptic-scale forcing. The modification to the latent heating in turn influences the evolution of the storm.

iii. Precipitation is enhanced in some regions and diminished in others on the windward side of the topography due to the convergence/divergence patterns imposed by the flow interaction with the topography. These patterns are dependent upon the synoptic scale flow characteristics of the landfalling storm.

4. Observational Requirements

A. Coastally-Trapped Disturbances

The central issue about the trapped nature of these disturbances and the associated hypotheses about the initiation, propagation, and decay dictate specific needs for synoptic-scale, mesoscale, and boundary layer observations in order to address these issues. The preliminary results from the June 9-11 1994 event are also important in helping to specify minimum sets of observations to address the most critical issues. As is evident in the hypotheses stated in the last section, coastally-trapped disturbances represent a mix of synoptic-scale forcing and mesoscale or marine layer responses as well as structure and forcing by the marine layer. Since most previous studies have focused on the evolution of sea-level pressure and surface winds and the dynamic hypotheses rest on changes in marine boundary layer depth, the most significant observational need is to define the relationship between synoptic scale induced pressure variation and those caused by marine boundary layer depth changes. With this in mind, the set of synoptic and mesoscale observations needed will be described.

Synoptic-scale Observations

Synoptic and larger mesoscale observations are required to characterize the three dimensional structure of the environment and forcing over the lifecycle of the disturbance. Ideally, three dimensional structure over much of the western U.S. and Eastern Pacific Ocean area at time intervals of 3 hours or less would be useful for defining the synoptic forcing at the onset and in detail throughout the lifecycle. This is not practical from an observational approach alone and should be coupled with data assimilation in mesoscale models to meet this need. Even in a data assimilation approach, some significant gaps in synoptic-scale observations exist in defining the forcing of these disturbances. The existing set of routine synoptic observations is shown in Fig. 7.

The most notable problem is the lack three dimensional structure over the ocean area. Evidence from the June 9-11, 1994 disturbance suggests that two critical issues need to be addressed from additional over ocean synoptic-scale observations. First as hypothesized in the last section, the initiation of the disturbance may be related to the southward advection of a frictionally generated potential vorticity plume. To establish the existance of this feature, winds and low-level thermal structure need to be defined offshore out to 135^o W and this needs to precede the development of the disturbance by 48 hours or possibly more. Second, the June 9-11, 1994 disturbance had the development of a cyclonic vortex in the lower troposphere off the coast from Pt. Conception. The position, intensity, and

evolution of this feature needs to be documented. An example of this feature in a model simulation of the 10 June 1994 case is shown in Fig. 8. These two structures suggest the need for vertical structure measurements from the coast out to 135° W extending from the Southern California bight region to the Oregon border. The temporal resolution is uncertain but 12 hourly or more frequently is probably of use for the period 48 hours prior to and throughout the lifecycle of the disturbance.

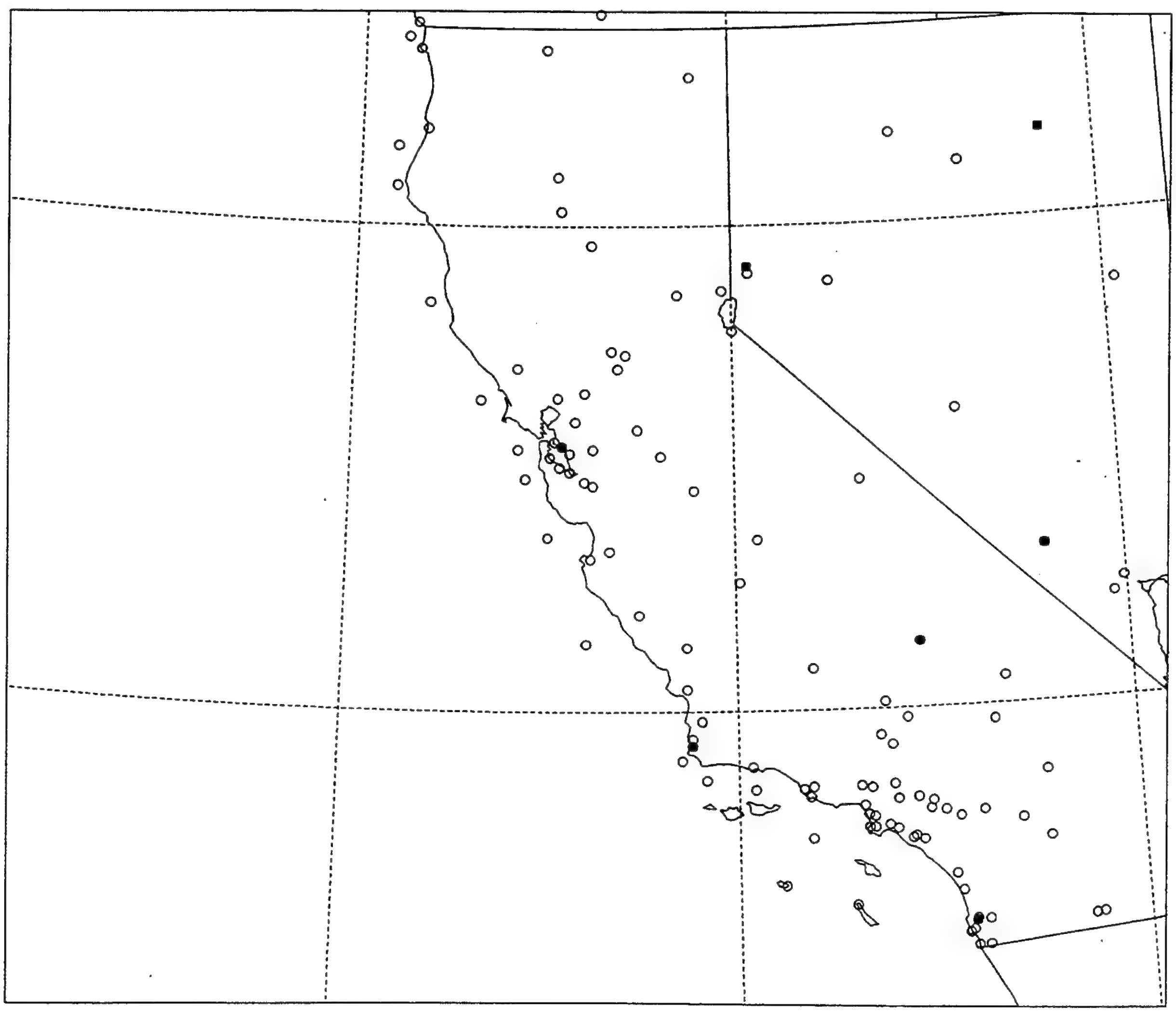


Fig. 7. Upper-air (dark squares) and surface observing (open circles) stations that routinely report over the western U.S. and eastern Pacific Ocean.

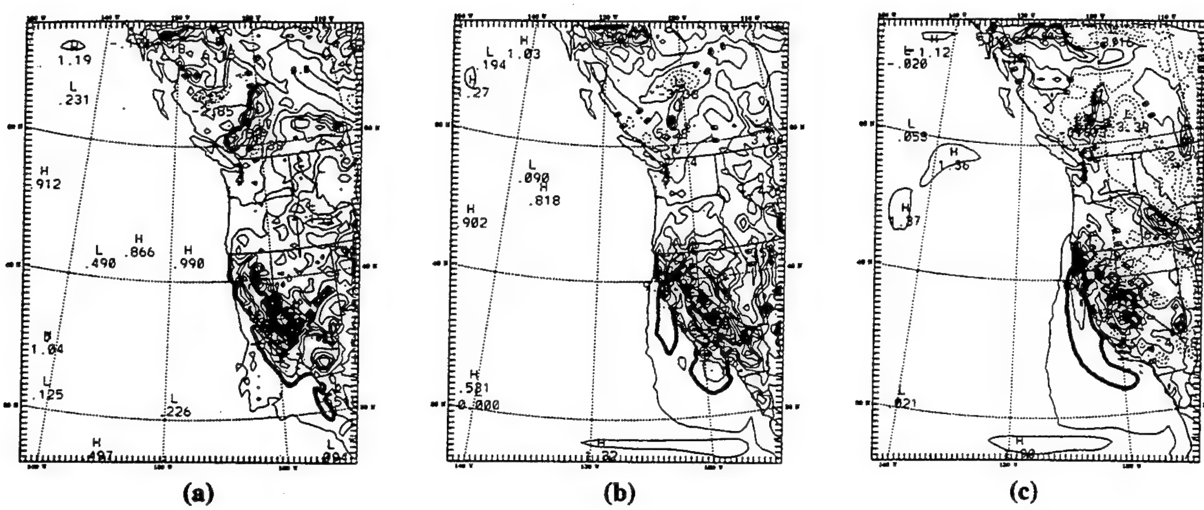
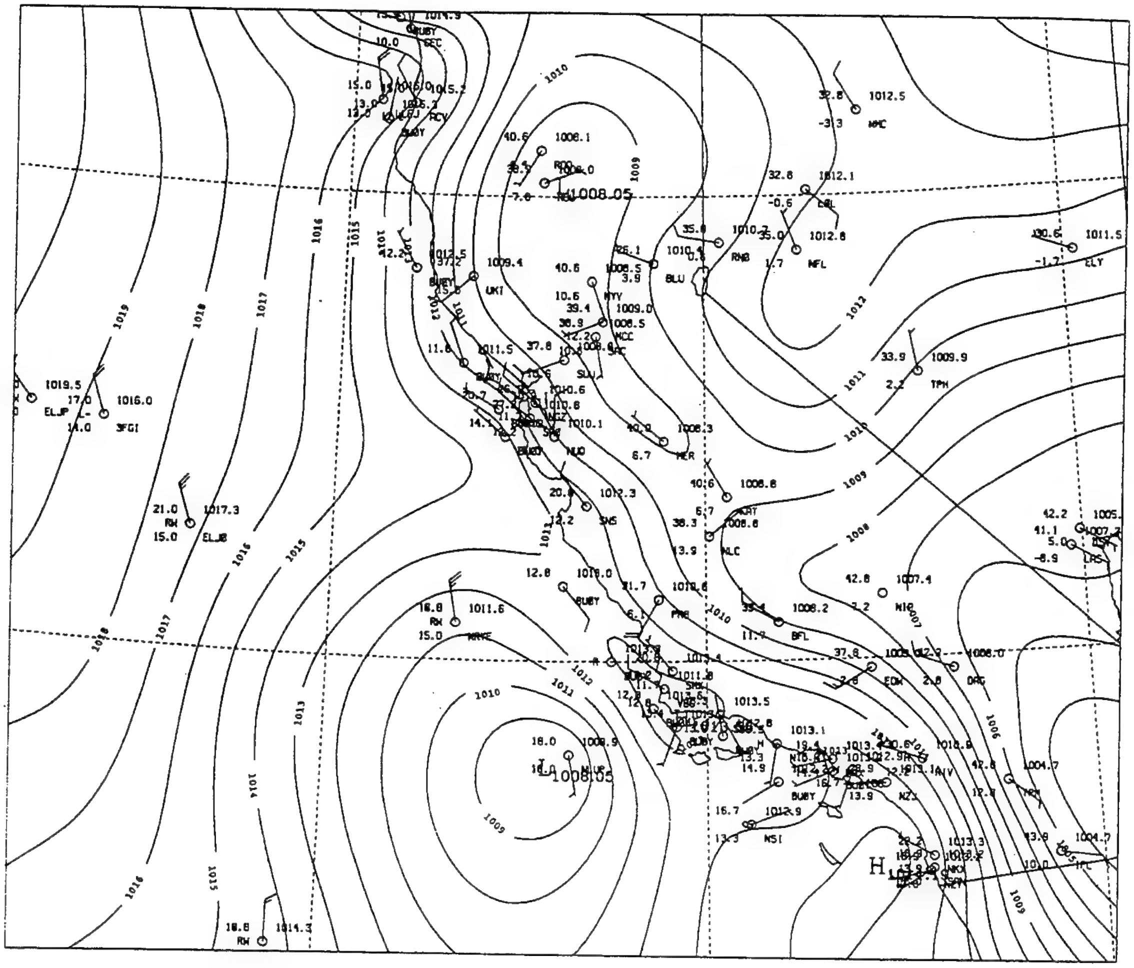


Fig. 8. Analyses of 970 mb potential vorticity from a model simulation that started at 0000 UTC 8 June 1994. The analyses at a) 0600 UTC 8 June, b) 0600 UTC 9 June, and c) 0000 UTC 10 June are shown with isopleth interval of 1 PVU and 2 PVU isopleth in bold. (From Persson et. al., 1996).

Sea-level pressure observations at hourly intervals over most of the Eastern Pacific Ocean region are needed to provide a more detailed depiction of the synoptic-scale evolution. These surface observations provide both a check on the model assimilated structure and a direct mapping of the low-level pressure gradients that force the marine boundary layer. The robustness of features such as the low pressure center that developed offshore during the June 9-11, 1994 case (Fig. 9) could be established with these observations. The generality of features such as this low pressure center are of central importance to the forcing of the coastally-trapped response and are difficult to define from the routine ship observations that often have substantial errors and typically only report at twelve hour intervals.



CONTOUR FROM 1004 TO 1020 BY 1

Fig. 9. Sea-level pressure analysis at 0000 UTC 11 June 1994. Contours every 1 mb.

The marine boundary layer depth and marine boundary layer winds need to be defined at 6 hour or less intervals over large areas of the Eastern Pacific Ocean off the California coast. These measurements are essential to define the relationship between the sea-level pressure and the marine boundary layer depth variations. In addition, the stratification and winds are required to define the existence of and evolution of the hypothesized potential vorticity plume. This structure can only practically be obtained through aircraft flights to map the marine boundary layer depth in an organized manner over the ocean region.

The structure of the atmosphere above the marine boundary layer is also important

to define the free atmosphere's contribution to the sea-level pressure changes and the evolution of synoptic features aloft. To be consistent with the vertical sampling over the land areas, twelve hourly measurements are needed of the winds, temperature, and geopotential heights over a wide area. These measurements are best accomplished through dropsondes using a high flying aircraft to cover a large area.

Mesoscale and Boundary Layer Observations

Mesoscale and boundary layer observations are needed primarily in the coastal zone to better define the response of the atmosphere in the coastal region as the coastally-trapped disturbance is initiated and evolves. Several critical questions depend upon detailed knowledge of the winds, thermal, and cloud structures as well as the marine boundary layer depth over an extended area along the coast. These observations are required to establish the trapped nature of the disturbance as well as the controlling dynamics and influence of the synoptic-scale on those dynamics. Observations within this scale can not be adequately used in data assimilation approaches and should therefore be fairly complete to define the complete structure and temporal evolution. Many of the required measurements are similar to those listed above for the synoptic-scale.

Cross and along coast measurements of the marine boundary layer depth are essential to characterize the trapped nature and the fundamental dynamics of these disturbances. The contribution of marine boundary layer depth gradients in the along coast direction to the sea-level pressure gradient are required to understand the relative roles of the Kelvin wave and/or rotating gravity current processes and the synoptic and mesoscale variations above the marine boundary layer. These along coast variations in the marine boundary layer depth can be effectively accomplished using coastal wind profilers with RASS. The along-coast spacing of the profilers should probably be less than 150-100 km. Cross-coast measurements of the marine boundary layer depth prior to, during, and after a coastally-trapped disturbance has passed are needed to identify the Kelvin wave, gravity current, or trapped mesoscale nature of the disturbance. The slope and offshore length scale of the marine boundary layer depth variations provide direct insight into the trapped nature of these events. The only practical method to obtain this information is through cross coast aircraft flights throughout the event.

The distribution of lower atmospheric winds are needed to define the mesoscale divergence patterns and vorticity patterns that arise through various aspects of the forcing. The cross-coast structure of the wind field is useful to understand the trapped nature of the disturbance. The distribution of the low-level winds is useful to understand how

low-level convergence is generated and acts to force the marine boundary layer up and down. The relationships are likely to be different in Kelvin wave or synoptically driven disturbances, especailly in their temporal evolution preceding and during the event. These measurements can only be obtained through aircraft measurements covering the coastal region both before and during the event.

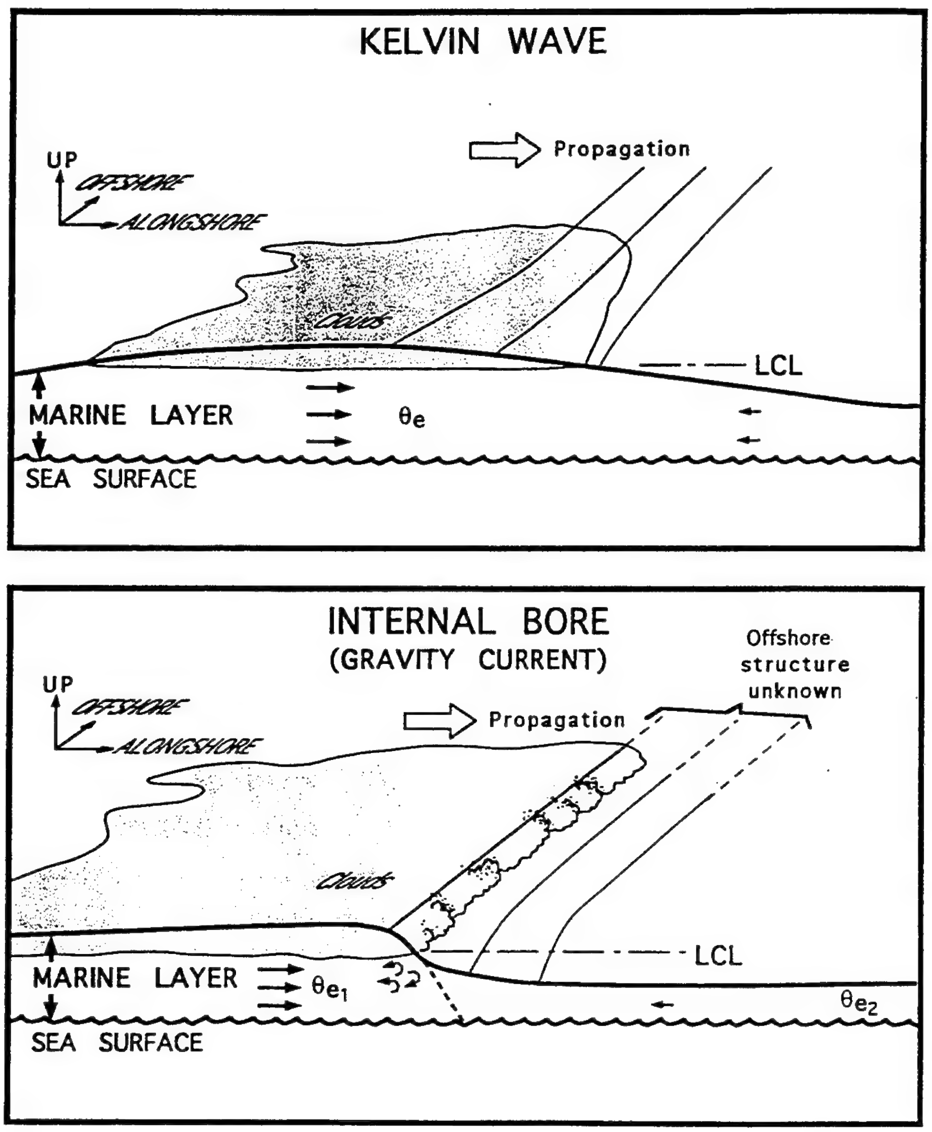


Fig. 10. Along-coast sketch of the hypothesized mesoscale structure of a coastally-trapped Kelvin wave or gravity current. (Courtesy of John Bane.)

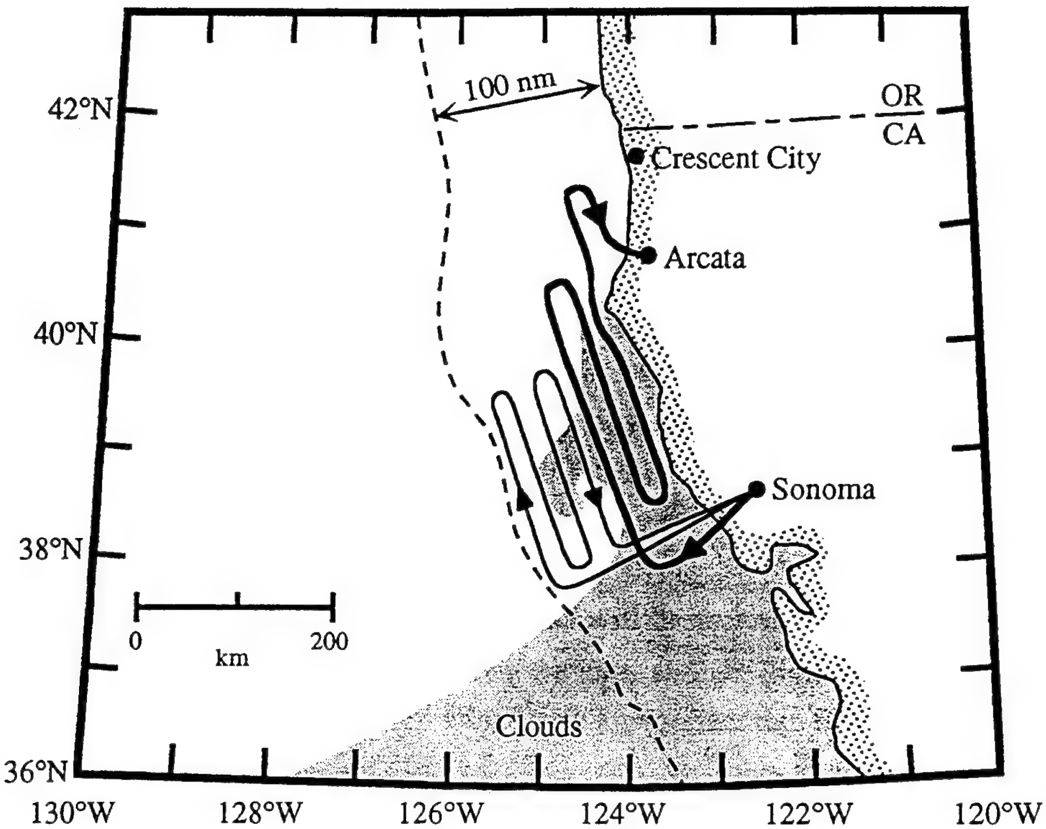


Fig. 11. Sample aircraft tracks through a coastally-trapped disturbance and its associated stratus cloud. (Courtesy of John Bane.)

Finally, turbulent fluxes in select portions of the disturbance and the atmosphere preceding the disturbance are needed to define the surface forcing of these events. The removal of the mixed layer prior to the event along the northern portion of the coast may be dependent upon turbulent processes. In addition, the rate of frictional spin-down is needed to understand whether decay is a spin-down process or whether the forcing simply decays. These measurements can only be achieved through aircraft measurements using an aircraft equipped with turbulence systems.

B. Storm Interaction

The observations required to address the issues related to storm-coast interactions have formed the basis for planning of intensive field operations in December 1995. These plans are essentially complete and are briefly summarized here.

The modification of landfalling storms by coastal terrain will be studied using combined observational/modelling case studies. The events of interest are usually complex, with an interplay between orographic and diabatic effects, and often with a rapidly-changing background state. The diagnosis of the dynamics in these situations can generally best be done using the output from high-resolution NWP simulations, but these simulations are compromised if there is insufficient data for an adequate initialization, or if the results are not properly validated. Therefore two kinds of data are required: observations of the synoptic-scale flow associated with the storm 12-24 hours before landfall, and detailed, mesoscale measurements in the vicinity of the coast as the storm makes landfall. The former will be collected by an Air Force Reserve WC-130 via dropwinsonde surveys; the latter will be collected by a NOAA WP-3D. The suite of measurements to be collected by the P-3 includes dropwinsonde data (including over land), flight-level meteorological observations, reflectivity and Doppler wind measurements from lower fuselage and tail radars, cloud microphysical measurements, and high-frequency wind, temperature and humidity fluctuations. These measurements will be used to document the interplay between the mesoscale flow structures forced by the terrain and sub-grid scale phenomena such as cloud processes and turbulence. Aircraft are ideally suited for carrying out this work because of their logistical flexibility, i.e., their ability to go when and where the weather dictates.

Two different strategies can be adopted by the P-3 for the coastal flights. If precipitation is occurring along the coastal terrain, the flight(s) will be arranged to map the evolution of coastally-trapped features as storms/fronts approach and make landfall. Alternatively, if precipitation is absent or spotty at the coast, the flight(s) will involve following a front or storm feature onto the coast. The former strategy is preferred for the sake of simplicity and tractability, but because of the amount and importance of the wind data that can be collected remotely by the tail Doppler radar (which is effective only in regions of precipitation), the weather may at times dictate the latter strategy. The pilot field operations in December 1993 have been used to refine the details of the sampling methods. Given the amount of research flight hours available, and typical conditions along the Pacific Northwest coast in December, this experiment should be able to collect detailed observations of 5-6 storms/fronts in the coastal zone.

C. Summary

These observational requirements highlight the necessary observations to make significant progress on the science issues and hypotheses listed in this document. These observational requirements may not be completely exhaustive nor do they reflect the actual observing strategies for the up-coming field programs. Separate operational plans that detail actual observing plans are under preparation for use during the field programs.

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